

Double-parton scattering contribution to production of jet pairs with large rapidity separation at the LHC

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(Dated: March 12, 2014)

Abstract

We discuss production of four-jet final state $pp \rightarrow jjjjX$ in proton-proton collisions at the LHC through the mechanism of double-parton scattering (DPS) in the context of jets with large rapidity separation. The DPS contributions are calculated within the so-called factorized Ansatz and each step of DPS is calculated in the LO collinear approximation. The LO pQCD calculations are shown to give a reasonably good description of recent CMS and ATLAS data on inclusive jet production and therefore this formalism can be used to reliably estimate the DPS effects. Relative contribution of DPS is growing at large rapidity distance between jets. This is consistent with our experience from previous studies of double-parton scattering effects in the case of open and hidden charm production. The calculated differential cross sections as a function of rapidity distance between the most remote in rapidity jets are compared with recent results of LL and NLL BFKL calculations for Mueller-Navelet (MN) jet production at $\sqrt{s} = 7$ TeV. The DPS contribution to widely rapidity separated jet production is carefully studied for the present energy $\sqrt{s} = 7$ TeV and also at the nominal LHC energy $\sqrt{s} = 14$ TeV and in different ranges of jet transverse momenta. The differential cross section as a function of dijet transverse momenta as well as two-dimensional $(p_T(y_{min}) \times p_T(y_{max}))$ -plane correlations for DPS mechanism are also presented. Some ideas how the DPS effects could be studied in the case of double dijet production are suggested.

PACS numbers: 13.87.Ce, 14.65.Dw

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I. INTRODUCTION

It is reasonable to expect that large-rapidity-distance jets are more decorrelated in azimuth than jets placed close in rapidity. About 25 years ago Mueller and Navelet predicted strong decorrelation in relative azimuthal angle [1] of such jets due to exchange of the BFKL ladder between quarks (partons). The generic picture is presented in diagram (a) of Fig. 1. In a bit simplified picture quarks/antiquarks/gluons are emitted forward and backward, whereas gluons emitted along the ladder populate rapidity regions in between. Due to diffusion along the exchange ladder the correlation between the most forward and the most backward jets is small. This was a simple picture obtained within leading-logarithmic BFKL formalism [1–6]. In Ref. [7] so-called consistency constrain was imposed in addition. Recent higher-order BFKL calculation slightly modified this simple picture [8–17] leading to smaller azimuthal decorrelation in rapidity. Recently the NLL corrections were calculated both to the Green’s function and to the jet vertices. The effect of the NLL correction is large and leads to significant lowering of the cross section. So far only averaged values of $\langle \cos(n\phi_{jj}) \rangle$ over available phase space or even their ratios were studied experimentally [18]. More detailed studies are necessary to verify this type of calculations. In particular, the approach should reproduce dependence on the rapidity distance between the jets emitted in opposite hemispheres and more detailed associated dependences on transverse momenta of the jets. Large-rapidity-distance jets can be produced only at high energies where the rapidity span is large due to kinematics. A first experimental trial of search for the MN jets was made by the D0 collaboration [19]. In their study rapidity distance between jets was limited to 5.5 units only. Nonetheless they have observed a broadening of the ϕ_{jj} distribution with growing rapidity distance between jets. However, theoretical interpretation of the broadening is not clear. The dijet azimuthal correlations were also studied in collinear next-to-leading order approximation [20]. The LHC opens new possibility to study the decorrelation effect quantitatively. First experimental data measured at $\sqrt{s} = 7$ TeV are expected soon [21].

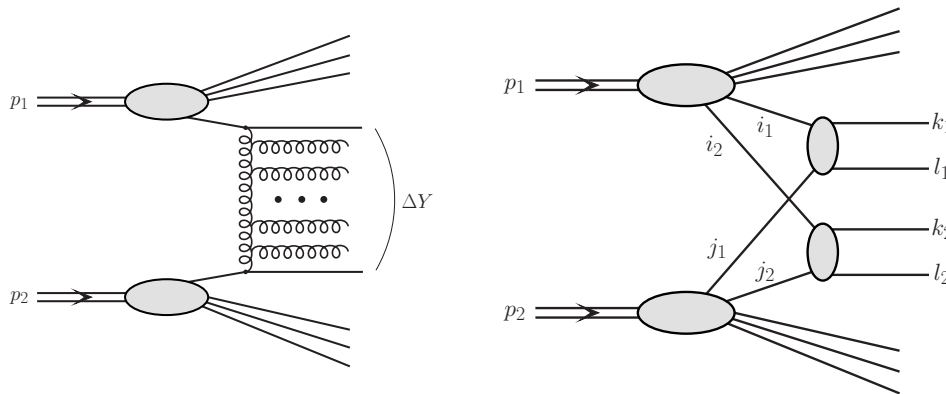


FIG. 1: A diagrammatic representation of the Mueller-Navelet jet production (left diagram) and of the double parton scattering mechanism (right diagram).

On the other hand recent studies of multiparton interactions have shown that they may easily produce objects which are emitted far in rapidity. Good example is production of $c\bar{c}c\bar{c}$ [22–24] or inclusive production of two J/ψ mesons [25, 26]. Here we wish to concentrate on four-jet double-parton scattering (DPS) production with large distances between jets (see diagram (b) in Fig. 1). Several suggestions how to separate four-jet DPS contribution from

SPS contribution at midrapidities were discussed in Ref. [27].

In the present first exploratory study we shall make first estimate of the DPS effects for jets with large rapidity separation within leading-order collinear approximation. Already this approximation will allow us to nicely illustrate the generic situation. We shall focus on distribution in rapidity distance of the most-rapidity-distant jets. The DPS result will be compared to the distribution in rapidity distance for standard $2 \rightarrow 2$ single parton scattering (SPS) pQCD dijet calculation. We shall identify the dominant partonic subprocesses important to understand the situation in the small but interesting corner of the phase space. The calculation of distributions in rapidity distance will be supplemented by the analysis of correlations in the two-dimensional space of the transverse momenta of the two widely separated jets or by calculation of distributions in transverse momentum imbalance of the jets or correlations in azimuthal angle between them.

II. BASIC FORMALISM

In the present calculation all partonic cross sections ($ij \rightarrow kl$) are calculated in leading-order only. The cross section for dijet production can be written then as:

$$\frac{d\sigma(ij \rightarrow kl)}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 f_i(x_1, \mu^2) x_2 f_j(x_2, \mu^2) \overline{|\mathcal{M}_{ij \rightarrow kl}|^2}, \quad (2.1)$$

where y_1, y_2 are rapidities of the two jets (k and l) and p_t is transverse momentum of one of them (they are identical). The parton distributions are evaluated at $x_1 = \frac{p_t}{\sqrt{s}}(\exp(y_1) + \exp(y_2))$, $x_2 = \frac{p_t}{\sqrt{s}}(\exp(-y_1) + \exp(-y_2))$ and $\mu^2 = p_t^2$ is used as factorization and renormalization scale.

In our calculations we include all leading-order $ij \rightarrow kl$ partonic subprocesses (see e.g. [28, 29]). The K -factor for dijet production is rather small, of the order of $1.1 - 1.3$ (see e.g. [30, 31]), but can be easily incorporated in our calculations. Below we shall show that already the leading-order approach gives results in sufficiently reasonable agreement with recent ATLAS [32] and CMS [33] data.

This simplified leading-order approach can, however be, used conveniently in our first estimate of DPS differential cross sections for jets widely separated in rapidity. In analogy to the production of $c\bar{c}c\bar{c}$ (see e. g. [22]) one can write:

$$\frac{d\sigma^{DPS}(pp \rightarrow 4\text{jets } X)}{dy_1 dy_2 d^2 p_{1t} dy_3 dy_4 d^2 p_{2t}} = \sum_{\substack{i_1, j_1, k_1, l_1 \\ i_2, j_2, k_2, l_2}} \frac{\mathcal{C}}{\sigma_{eff}} \frac{d\sigma(i_1 j_1 \rightarrow k_1 l_1)}{dy_1 dy_2 d^2 p_{1t}} \frac{d\sigma(i_2 j_2 \rightarrow k_2 l_2)}{dy_3 dy_4 d^2 p_{2t}}, \quad (2.2)$$

where $\mathcal{C} = \begin{cases} \frac{1}{2} & \text{if } i_1 j_1 = i_2 j_2 \wedge k_1 l_1 = k_2 l_2 \\ 1 & \text{if } i_1 j_1 \neq i_2 j_2 \vee k_1 l_1 \neq k_2 l_2 \end{cases}$ and partons $i, j, k, l = g, u, d, s, \bar{u}, \bar{d}, \bar{s}$. The combinatorial factors include identity of the two subprocesses. Each step of the DPS is calculated in the leading-order approach (see Eq.(2.1)). The quantity σ_{eff} has dimension of cross section and has a simple interpretation in the impact parameter representation [34]. Above y_1, y_2 and y_3, y_4 are rapidities of partons in first and second partonic subprocess, respectively. The p_{1t} and p_{2t} are respective transverse momenta.

Experimental data from the Tevatron [35] and the LHC [36–38] provide an estimate of σ_{eff} in the denominator of formula (2.2). As in our recent paper [24] we take $\sigma_{eff} = 15$ mb. A detailed analysis of σ_{eff} based on various experimental data can be found in Refs. [39, 40].

III. NUMERICAL RESULTS

Before we shall show our results for rapidity-distant-jet correlations we wish to verify the quality of description of observables for inclusive jet production. In Fig. 2 we show distributions in the jet transverse momentum for different intervals of jet (pseudo)rapidity (left panel) and distribution in jet (pseudo)rapidity for different intervals of jet transverse momentum (right panel). In this calculations we have used the MSTW08 PDFs [41]. The agreement with recent ATLAS data [32] is fairly reasonable which allows us to use the same distributions for first evaluation of the DPS effects for large rapidity distances between jets.

In Fig. 3 we compare our calculation with the CMS data [33]. In addition, we show contributions of different partonic mechanisms. In all rapidity intervals the gluon-gluon and quark-gluon (gluon-quark) contributions clearly dominate over the other contributions and in practice it is sufficient to include only these subprocesses in further analysis.

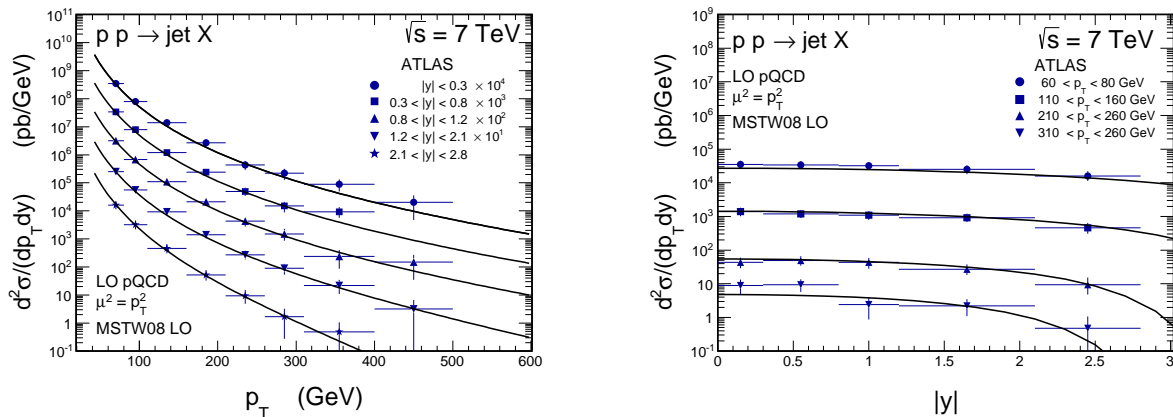


FIG. 2: Transverse momentum distribution of jets for different regions of the jet rapidity (left panel) and corresponding rapidity distribution of jets with different cuts in p_T as specified in the figure caption of the right panel. The theoretical calculations were performed with the MSTW08 set of parton distributions [41]. The data points were obtained by the ATLAS collaboration [32].

Now we shall proceed to the jets with large rapidity separation. In Fig. 4 we show distribution in the rapidity distance between two jets in leading-order collinear calculation and between the most distant jets in rapidity in the case of four DPS jets. In this calculation we have included cuts characteristic for the CMS experiment [21]: $y_1, y_2 \in (-4.7, 4.7)$, $p_{1t}, p_{2t} \in (35 \text{ GeV}, 60 \text{ GeV})$. For comparison we show also results for the LL and NLL BFKL calculation for MN jet from Ref. [15]. For this kinematics the DPS jets give sizeable relative contribution only at large rapidity distance. However, the four-jet (DPS) and dijet (LO SPS) final state can be easily distinguished and, in principle, one can concentrate on the DPS contribution which is interesting by itself. The NLL BFKL cross section (long-dashed line) is smaller than that for the LO collinear approach (short-dashed line).

As for the BFKL Mueller-Navelet jets the DPS contribution is growing with decreasing jet transverse momenta. Therefore let us now discuss results for even smaller transverse momenta. In Fig. 5 we show rapidity-distance distribution for even smaller lowest transverse momentum of the "jet". A measurement of such minijets may be, however, difficult. Now the DPS contribution may even exceed the standard SPS dijet contribution, especially at the nominal LHC energy. In Fig. 6 we lower in addition the upper limit for the jets. The

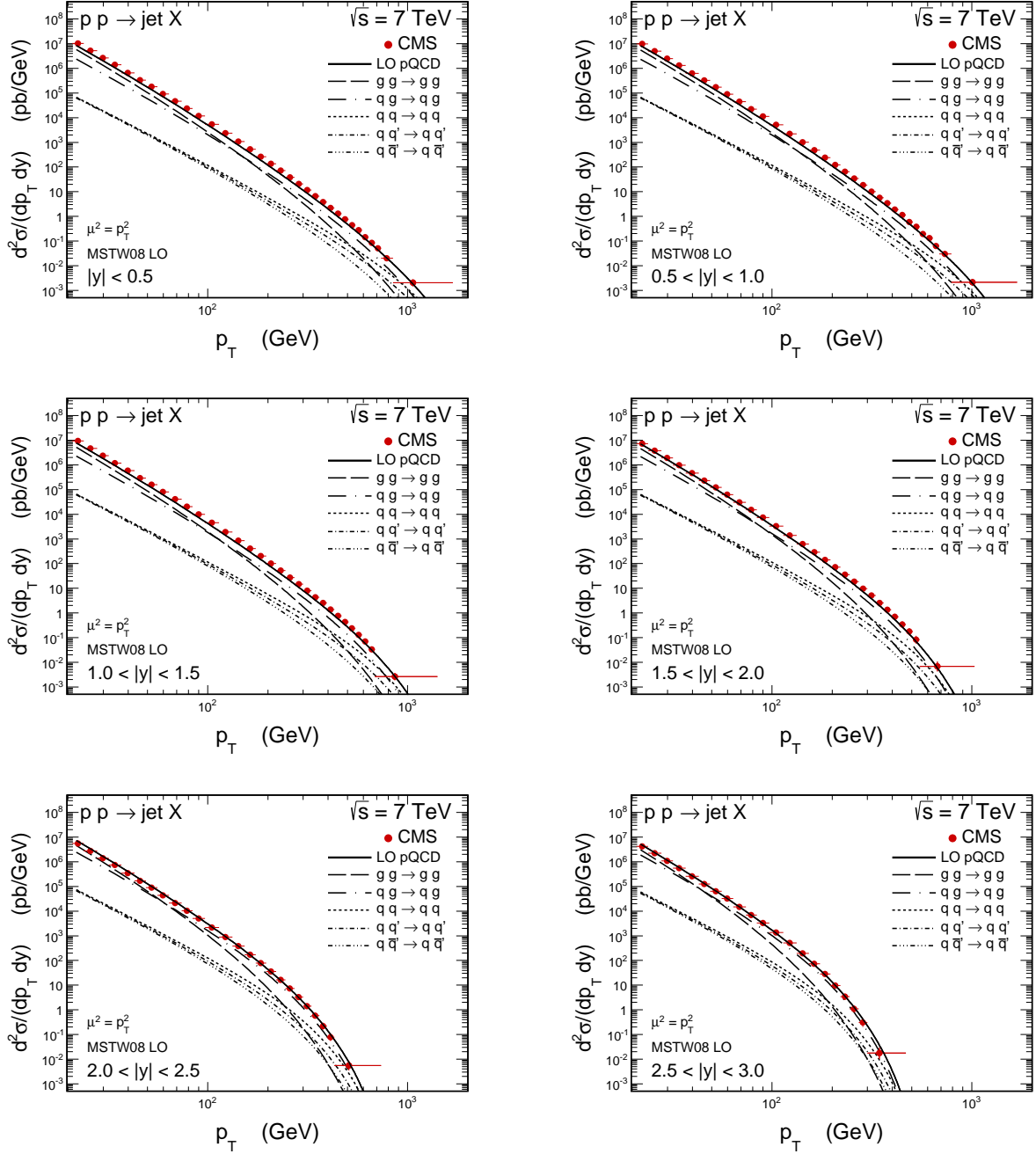


FIG. 3: The same as in the previous figure but now together with the CMS experimental data [33]. In addition, we show decomposition into different partonic components as explained in the figure caption.

situation does not improve further. How to measure such (mini)jets is an open issue. In principle, one could measure for instance correlations of semihard ($p_t \sim 10$ GeV) neutral pions with the help of so-called zero-degree calorimeters (ZDC) which are installed by all major LHC experiments. Other possibilities could be considered too.

Now we wish to concentrate ourselves on correlations between transverse momenta of the rapidity-distant jets. In our case the large-rapidity-distance jets are coming from different

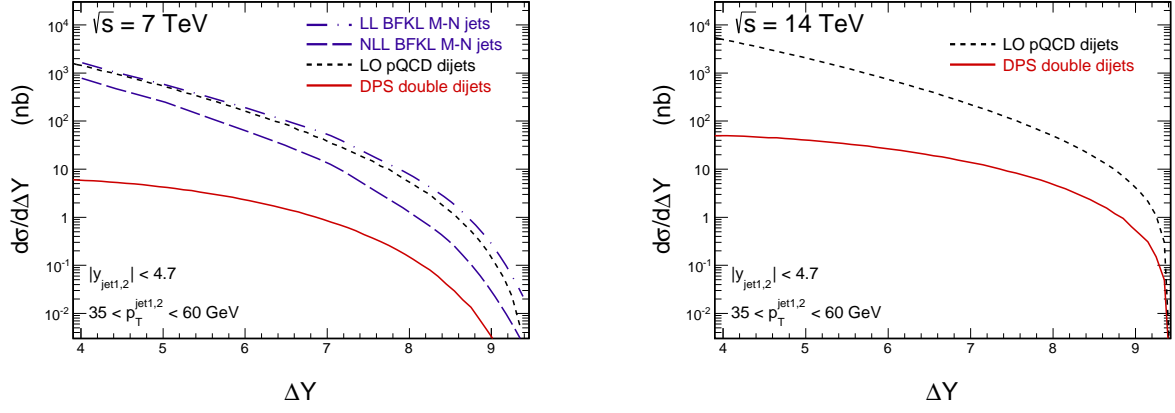


FIG. 4: Distribution in rapidity distance between jets ($35 \text{ GeV} < p_t < 60 \text{ GeV}$) with maximal (the most positive) and minimal (the most negative) rapidities. The collinear pQCD result is shown by the short-dashed line and the DPS result by the solid line for $\sqrt{s} = 7 \text{ TeV}$ (left panel) and $\sqrt{s} = 14 \text{ TeV}$ (right panel). For comparison we show also results for the classical BFKL Mueller-Navelet jets in leading-logarithm and next-to-leading-order logarithm approaches from Ref. [15].

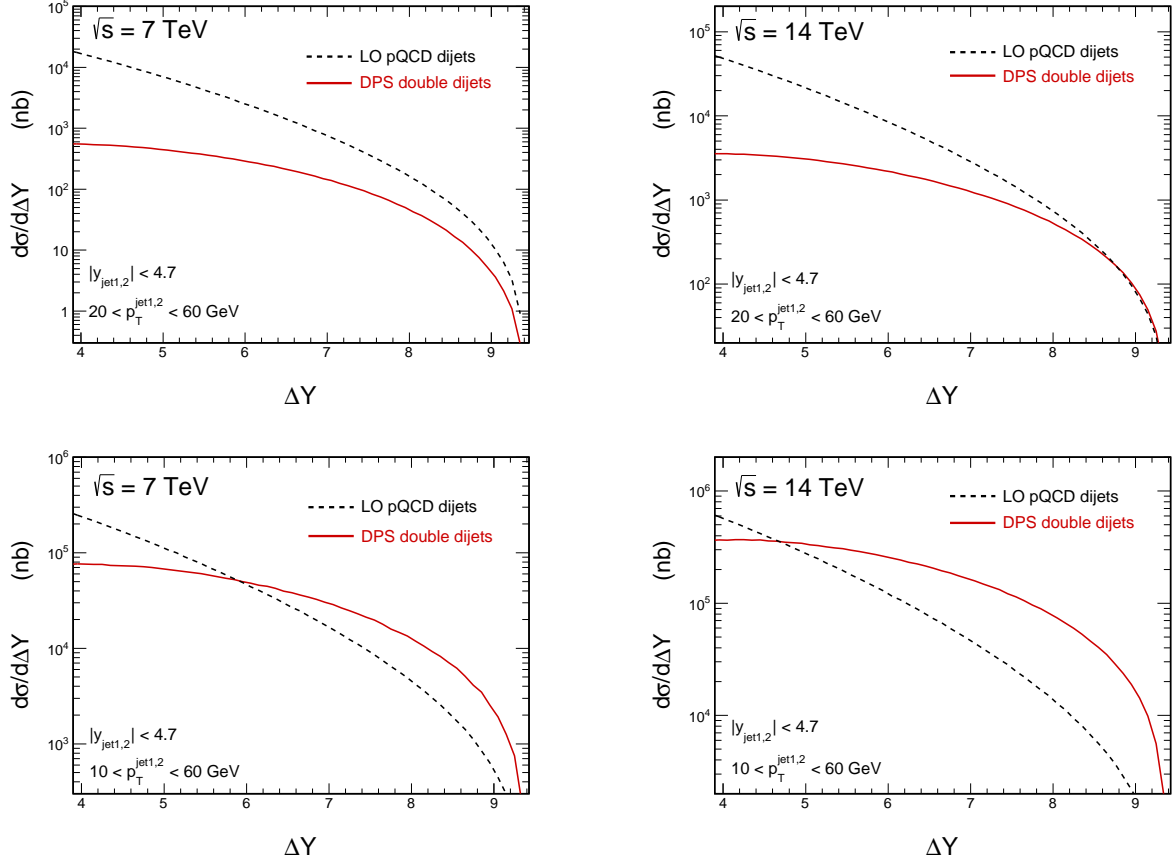


FIG. 5: The same as in the previous figure but now for somewhat smaller lower cut on minijet transverse momentum.

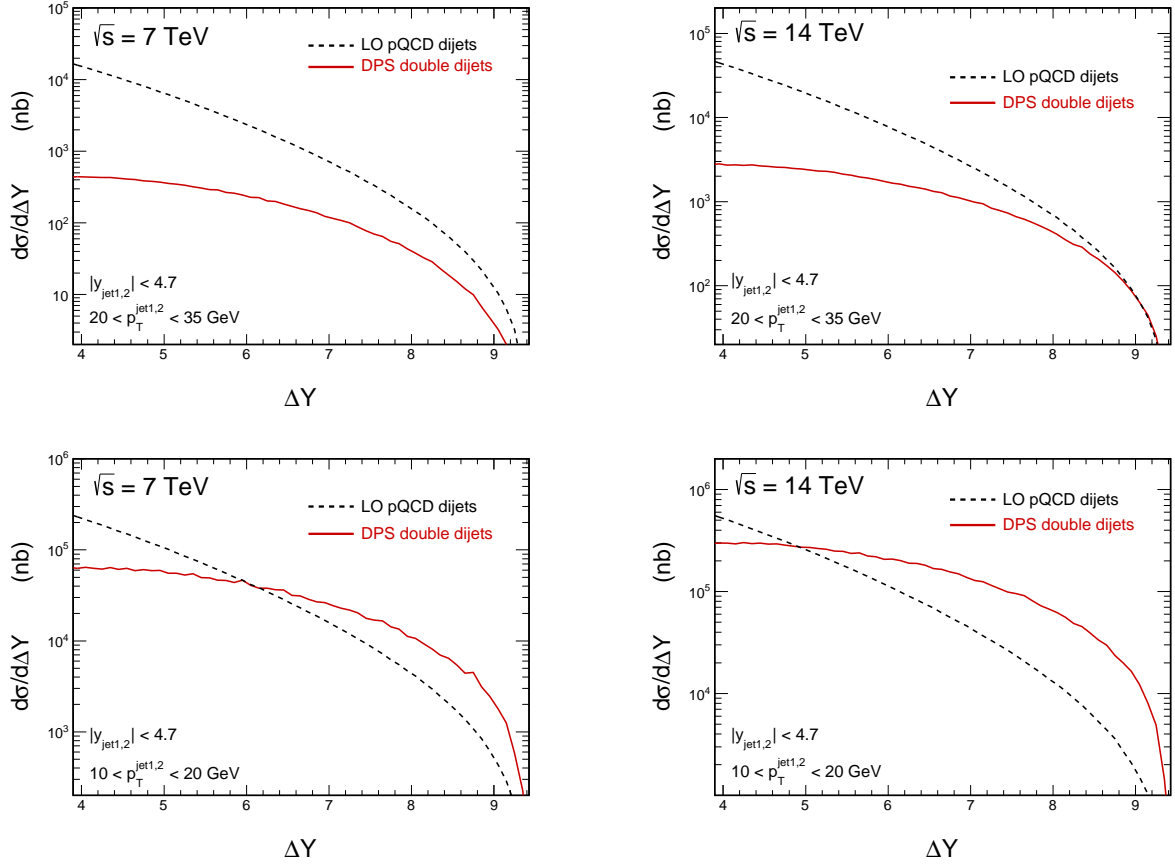


FIG. 6: The same as in the previous figures but now for somewhat smaller upper cut on minijet transverse momentum in addition.

partonic scatterings and are therefore quite uncorrelated. In Fig. 7 we present our results. The (p_{1t}, p_{2t}) distribution for the DPS mechanism is rather different than similar distributions for dijet SPS [42] and MN jets [4]. The dijets from the SPS as well as jets from the same partonic scattering in DPS are correlated along the $p_{1t} = p_{2t}$ diagonal [42] (see straight diagonal line in Fig. 7). In principle, one could eliminate this region by dedicated cuts. How the situation looks in the BFKL calculation can be already seen from simple LL calculation [4]. The CMS collaboration could make such two-dimensional studies. Another alternative are studies of distributions in the transverse momentum imbalance $\vec{p}_{t,sum} = \vec{p}_{1t} + \vec{p}_{2t}$ between the rapidity-distant jets. In Fig. 8 we show distributions for full range of rapidity distances (left panel) as well as for large-rapidity-distance jets (right panel). The DPS mechanism generates situations with large transverse momentum imbalance. This could be used in addition to enhance the content of DPS effects by taking a lower cut on the dijet imbalance. The transverse momentum imbalance for jets remote in rapidity is bigger than that for jets close in rapidity. The corresponding distribution for Mueller-Navelet jets has maximum at $p_{t,sum} \sim 0$. It would be interesting to calculate the transverse momentum imbalance also for SPS dijets as well as for the Mueller-Navelet jets. This clearly goes beyond the scope of this short note.

Finally we wish to discuss azimuthal correlations between the jets distant in rapidity. The azimuthal angle distributions for the Mueller-Navelet jets were calculated by many groups

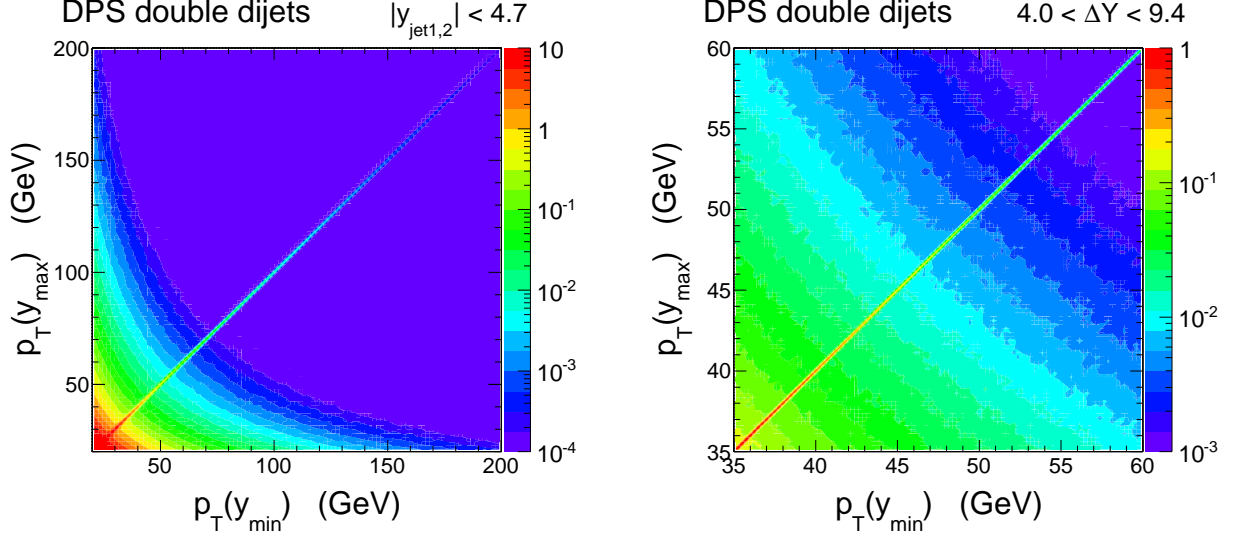


FIG. 7: The double-differential distribution in transverse momenta of jet with minimal ($p_T(y_{\text{min}})$) and maximal ($p_T(y_{\text{max}})$) rapidities. In the left panel we show the result for the full range of rapidities and in the right panel only for large rapidity separations as defined previously.

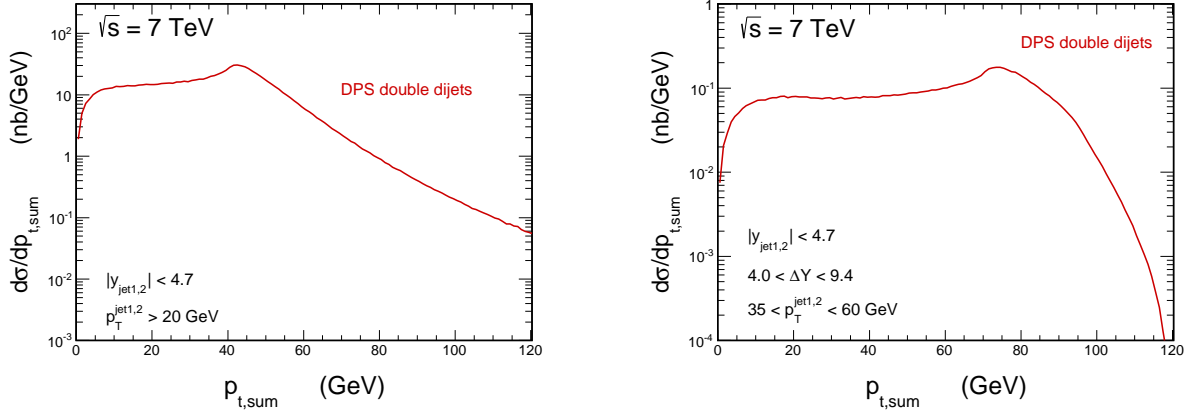


FIG. 8: Distribution in transverse momentum imbalance (vector sum of transverse momenta of jets) between the jets with "minimal" and "maximal" rapidities.

and we will not repeat such calculations here. The DPS jets are fully uncorrelated, at least in our approach. This is expected to be different for the SPS dijets (delta function $\delta(\phi - \pi)$ in the leading-order collinear approach) as well as for the classical Mueller-Navelet jets. The SPS dijet azimuthal correlations as well as the transverse momentum imbalance distribution could be easily calculated in the k_t -factorization approach [42–46]. In this approach one avoids singularities present in the fixed-order collinear approach.

A contamination of the large-rapidity-distance jets by the DPS effects may distort the information obtained by comparison with the BFKL calculation. This will be a subject of our future studies.

IV. CONCLUSIONS

In the present letter we have discussed how the double-parton scattering effects may contribute to large-rapidity-distance dijet correlations. The present exploratory calculation has been performed in leading-order approximation to understand and explore the general situation. This means that also each step of DPS was calculated in collinear pQCD leading-order. We have shown that already leading-order calculation provides quite adequate description of inclusive jet production when confronted with recent results obtained by the ATLAS and CMS collaborations. We have identified the dominant partonic pQCD subprocesses relevant for the production of jets with large rapidity distance.

We have concentrated ourselves on distributions in rapidity distance between the most-distant jets in rapidity. The results of the dijet SPS mechanism have been compared to the DPS mechanism. We have performed calculations relevant for planned CMS analysis. The contribution of the DPS mechanism increases with increasing distance in rapidity between jets. This is analogous to similar observations made already for the production of $c\bar{c}c\bar{c}$ [22–24] and $J/\psi J/\psi$ mesons [25, 26]. For comparison we have also shown some recent predictions of the Mueller-Navelet jets in the LL and NLL BFKL framework from the literature. For the CMS configuration our DPS contribution is smaller than the SPS dijet contribution even at high rapidity distances and only slightly smaller than that for the NLL BFKL calculation known from the literature. The DPS final state topology is clearly different than that for the SPS dijets (four versus two jets) which may help to disentangle the two mechanisms experimentally. Of course SPS three- and four-jet final states should be included in more refined analyses of distributions in rapidity distance.

We have shown that the relative effect of DPS could be increased by lowering the transverse momenta of jets but such measurements can be difficult if not impossible. Alternatively one could study correlations of semihard pions distant in rapidity. Correlations of two neutral pions could be done, at least in principle, with the help of zero-degree calorimeters present at each main detectors at the LHC. This type of studies requires further analyses taking into account also hadronization effects.

The DPS effects are interesting not only in the context how they contribute to distribution in rapidity distance but *per se*. One could make use of correlations in jet transverse momenta, jet imbalance and azimuthal correlations to enhance or lower the contribution of DPS. Further detailed Monte Carlo studies are required to settle real experimental program of such studies.

Acknowledgments

This work was supported in part by the Polish grant DEC-2011/01/B/ST2/04535 as well as by the Centre for Innovation and Transfer of Natural Sciences and Engineering Knowledge in Rzeszów.

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